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A survey of optical communications

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RESEARCH DEPARTMENT

A SURVEY OF OPTICAL COMMUNICATIONS

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A SURVEY OF OPTICAL COMMUNICATIONS

SUMMARY

The general present-day development of optical communications is discussed, as well as that of each link in an optical communication chain, viz. transmitters (lasers), modulators, transmission media (waveguides or the atmosphere) and detectors. The basic requirements of transmitter power output and detector efficiency in relation to signal to noise ratio are considered briefly. Optical links will become an engineering reality in the future and broadcasting applications could be found for them.

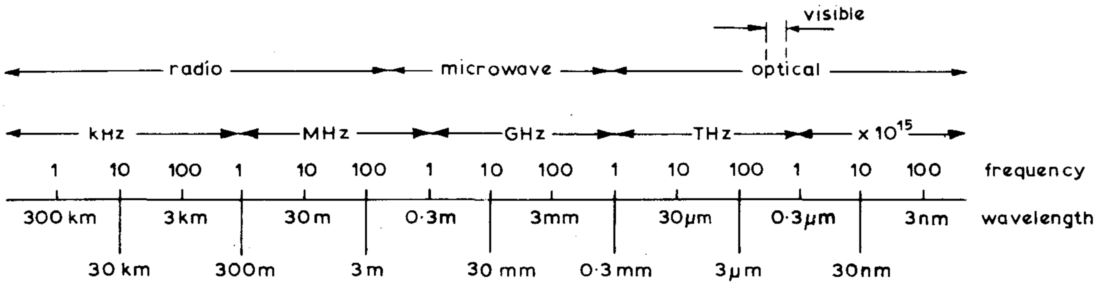

Fig. 1 - The electromagnetic spectrum

1. INTRODUCTION

In this report the term 'optical communications' denotes technical means for carrying information as modulation of a coherent beam of electromagnetic waves at optical frequencies. Historically light is one of the oldest media for communication over distances. But it has only recently become possible, with the development of the laser principle to modulate a beam of light with a signal as a radio carrier is modulated by a television or telephony signal. Optical frequencies extend from about 10^{13} to 10^{17} Hz and thus include infra-red as well as visible parts of the spectrum (see Fig. 1). It is well known that the amount of information that can be transmitted on a carrier wave increases with the bandwidth available. Conventional light (from a lamp) can be modulated, but the modulation bandwidth is limited and the noise level high, since the effective carrier is a band of noise. A laser transmission, however, can be concentrated into a very narrow beam, and is a coherent source capable of carrying information as radio frequency carrier waves do. These theoretical advantages of coherence combined with narrow beam and wide bandwidth have stimulated world-wide research into optical communication. Much development of materials and systems is needed, however, before optical communications can in practice compete with radio-frequency communications. Nevertheless, rapid progress can be expected because of the stimulus of space-communication and defence requirements.

Various possible systems and devices are briefly discussed here, particularly in relation to possible applications within the BBC in both the near and the more distant future. Theoretically possible performance is indicated.

2. COMMUNICATIONS CHAIN

An optical communications chain is shown in Fig. 2. Each consituent unit can take a number of forms: the laser may be a gas, liquid or semiconductor type; the modulation may be amplitude, frequency or pulse-code, the communication medium may be free space or a guided medium such as an optical fibre or waveguide; the detection system may be a simple photo-detector or a heterodyne system. For example, a system for carrying p.c.m. television might consist of a pulsed gallium-arsenide laser firing into a length of optical fibre waveguide, the signal being detected at the far end by a fast photomultiplier. Each section in the communications chain is distinct and will be considered separately.

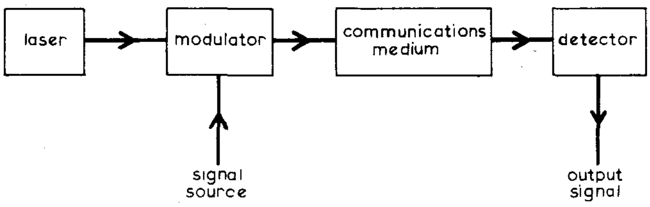

Fig. 2 - The optical communications chain

3. LASERS

3.1. General Description

Laser action will be described only briefly here; for fuller explanation see Reference 1. The laser generates an intense narrow beam of coherent light by stimulated emission of radiation. Since light emitted from different parts of a coherent source has constant phase, a large part of the original energy can be concentrated into a very narrow beam and directed at distant objects with negligible divergence.

In order to generate a coherent beam, atoms of the laser material which are in a low-energy level must be forced into a higher energy level. Once they are in this higher level, the atoms can be stimulated to lose some of their energy and to emit radiation which will be in phase with, and in the same direction as, the stimulating radiation. This new radiation is reflected in some form of cavity and stimulates more radiation, thus achieving a continuous output by positive feedback. In many lasers the cavity consists of mirrors, one of which is partially transparent so that some of the radiation generated escapes from the cavity to form a beam of coherent light. However the operation of practical lasers is considerably more complicated than the simple picture given above.

Laser oscillations have been observed in numerous materials including gases, crystalline solids, glasses, liquids, and semiconductors. For optical communications only the gas and semiconductor lasers are now practical, but lasers of the other types may be developed.

3.2. Gas Lasers

The first laser to be developed was the crystalline solid ruby laser but the most common existing practical type is the helium-neon (He-Ne) gas laser, with stimulated emission of red light at a wavelength of 0·6328 microns*. A mixture of helium and neon is enclosed in a glass tube with mirrors placed accurately at the ends. An electric discharge which causes collisions between electrons and atoms starts emission. The modern He-Ne laser, together with its excitation equipment and power supply, can be made into a compact instrument capable of generating up to 100 watts continuous output. The other gas laser which might be competitive in the near future is the carbon-dioxide laser which can generate high powers at a wavelength of 10 microns. All the gas lasers operate basically in a continuous mode. Pulse operation is difficult because of the time required to start a discharge in the gas, although a recently developed technique of mode-locking may overcome this (see Section 3.4).

The main advantage of a gas laser is its ability to maintain a single frequency output with a stability of a few parts in 10^8; no other type of laser has this attribute. Noise output is generally negligible. The He-Ne laser is readily available commercially and is a very useful laboratory device. Unfortunately from a communications point of view, it is neither mechanically rugged nor very reliable. The mirrors must be precisely placed in order to focus the beam accurately; a sudden blow is likely to upset them. Existing discharge tubes have an average life of only about 1000 hours. This laser therefore cannot be used for a long term communications installation, but it might be used in a small link where reliability is not of prime importance.

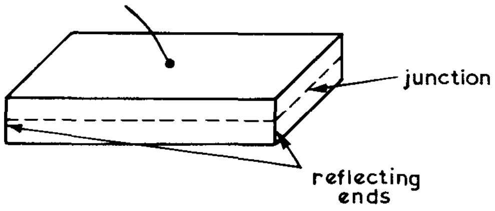

Fig. 3 - Schematic diagram of a p.n. junction GaAs laser. The laser beam is emitted near the junction from the reflecting ends.

3.3. Semiconductor Lasers

Semiconductors can be made to behave as lasers if the material is irradiated so that electrons move from the valency band to the conduction band and start stimulated emission. The most important semiconductor is gallium-arsenide (GaAs) with emission between 0·6 and 0·9 microns. A schematic diagram of a p-n junction GaAs laser is shown in Fig. 3. The resonator ends do not need to be coated because the refractive index of the material causes high internal reflection. Current is passed across the p-n junction to excite the atoms. The atoms can also be excited by electron beam, optical or avalanche pumping.

Laser action will not occur if the current is below a threshold value which increases as the temperature is raised. A typical laser has a threshold current of 10 A. The length of the laser is chosen so that it resonates at the wavelength of the desired mode, producing a beam with a bandwidth of about 0·1 nm. However, except near the threshold, single mode operation is difficult and a number of modes are propagated in the resonator, giving a spectrum of lines, about 0·2 nm apart, with amplitudes decreasing either side of the main mode. The noise in single mode lasers is very small, but the noise in each mode of a multimode laser is quite high, although there are correlations between the modes so that the noise in the output beam integrated over a wavelength is quite small again.

The GaAs laser is potentially ideal for communication purposes. The actual radiating element is only a few microns in length and is normally obtainable in a device about the size of a transistor. It requires only a low voltage d.c. power supply, has a turn-on time of a few nanoseconds, can be modulated by modulating the drive current and is extremely rugged and reliable. The principal disadvantage is that c.w. operation is only possible by cooling with liquid helium or nitrogen. This is because the series resistance of the GaAs laser absorbs light and the heat produced must be dissipated by cooling. This laser can be used in pulse operation at room temperature but even a pulse rate of only about 20 kHz requires very large currents. Another drawback is that the spectrum of modes would cause dispersion in any guiding structure. There is no theoretical reason why these drawbacks cannot be overcome but it may be some time before a room temperature, single mode, GaAs laser for continuous operation is practicable. When this occurs a very fast pulse rate will be possible and it should satisfy most of the requirements for the source of an optical communications chain. Other semiconductor lasers, such as yittrium aluminium garnet (yag) have been found to be less attractive than the GaAs laser.

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* 1 micron = 10^{-6} metres or 1μm.

3.4. Mode-Locked Lasers

A recently developed technique which may extend the usefulness of lasers for p.c.m. communication is mode-locking, or phase-locking, which produces a uniform series of fast pulses from a c.w. laser[5,8]. Potential repetition rates of more than 1·5 nanoseconds, rise times of a few picoseconds and high peak powers are feasible with either gas or semiconductor lasers. Although it is often thought of as a single frequency source, the laser can produce many discrete frequencies. (Normally the single mode is determined by the length of the resonant cavity.) A 'mode-locked' laser has a modulator incorporated inside the cavity in such a way that the laser oscillates with its wide band of frequencies in a fixed phase relationship and produces sharp pulses. Fourier analysis can represent a pulse by a series of discrete frequencies; mode-locking performs the reverse technique and synthesizes a pulse. The widths of the pulses generated are determined by the bandwidth of the laser; the wider the bandwidth the shorter the pulse. Thus the semiconductor laser, which generally has a wider source bandwidth than the gas laser, will produce sharper pulses, but with a low mark to space ratio.

4. MODULATING SYSTEMS AND METHODS

It is possible to modulate the amplitude, frequency or phase of a laser beam. For short-range atmospheric links a.m. or f.m. can be considered but for long-range links, pulse modulation is the most attractive. Pulse code modulation may be used for all ranges, because all the sections of an optical link are theoretically well suited to pulse operation. In a mode-locked laser the pulses are spaced relatively far apart in time so that by multiplexing several modulated sources optimum use of the available bandwidth can be achieved.

Modulation of a beam of light away from the source is achieved by passing it through a device where the optical waves interact with electric, magnetic or acoustic fields. There are three possible methods:

(a) Travelling-wave modulation
(b) Acoustic methods
(c) Electro-optic methods

In a travelling-wave modulator, light and microwaves are propagated together in a strip transmission line loaded with a non-linear crystal. The modulating-wave phase-velocity must be equal to the optical group velocity, so that the modulation is transferred from the microwave signal to the optical signal. This simple method unfortunately requires very high powers for a reasonable degree of modulation. In the acoustic method, the interaction occurs between the light beam and a sound beam carrying the modulation. The acoustic wave causes variations of pressure which change the refractive index. This system is very insensitive and has a poor bandwidth. Neither of these methods appears potentially useful for practical applications.

The transverse electro-optic method, on the other hand, is compact and offers the best performance. In this method, the principles of which have been known for nearly a century, the linear electro-optic effect occurring in certain crystals is used to alter the polarization of the incident light beam. The principles are shown in Fig. 4; more details are given in references 6 and 9. The beam

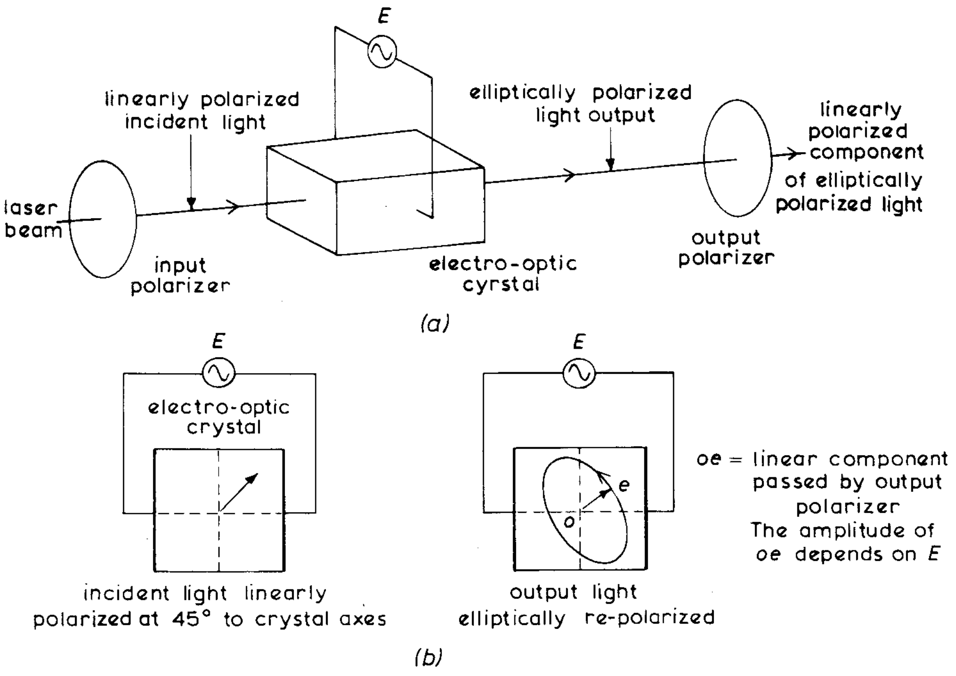
E
linearly polarized incident light
elliptically polarized light output
linearly polarized component of elliptically polarized light
laser beam
input polarizer
electro-optic cyrstal
output polarizer
(a)
E
electro-optic crystal
incident light linearly polarized at 45° to crystal axes
E
e
o
output light elliptically re-polarized
oe = linear component passed by output polarizer
The amplitude of oe depends on E
(b)

Fig. 4 - The electro-optic modulator

(*a*) Arrangement of component parts

(*b*) Principle of operation

from the laser passes through a polarizer which separates it into two components which are orthogonal in space. The transverse applied voltage on the electro-optic crystal changes the refractive index of the material anisotropically and alters the relative time phase of the two components in direct proportion to the applied voltage. By passing the elliptically-polarized output beam through another properly orientated polarizer, amplitude modulation is obtained. The amplitude modulation produced will have a non-linear characteristic and suffer from quadrature distortion unless the modulation depth is low. In practical modulators a number of crystals are cascaded to improve performance. To achieve 100% modulation without too much insertion loss a fairly high voltage is required. A frequency modulator using crystals in cavities has been described,[2] although this is more difficult to manufacture.

The electro-optic crystals may also be used to remove unwanted pulses in a pulse chain.[8] For instance, if a mode-locked laser is generating a continuous series of pulses, and a p.c.m. signal in synchronism is applied to the crystal, the presence of a pulse on the input p.c.m. signal can be made to rotate the polarization of the input beam through 90°, so that is passes through an output prism. But if the crystal is not pulsed electrically and the beam's polarization is not rotated, the beam is blocked by the output polarizer. In this way, the light pulses are coded to correspond with the p.c.m. input signal.

The two most common electro-optic crystals in use are potassium dihydrogen phosphate (KDP) and ammonium dihydrogen phosphate (ADP). KDP can only be obtained in small crystals but can be used to modulate a microwave carrier on to a laser beam. ADP can be obtained in large blocks and is easier to handle but bandwidths are presently limited to less than 100 MHz. Further development in materials will probably remove these restrictions and enable good modulators to be readily available.

5. COMMUNICATIONS MEDIUM

We next consider the various ways in which a modulated beam of coherent light may be sent from the transmitter to the receiver. There are four practical methods:

(a) Atmospheric link
(b) Confocal lens system
(c) Reflecting pipes
(d) Optical fibre guide

The last three differ from the atmospheric link in that the signal is guided along a structure, whereas in the atmosphere the beam is radiated from a high gain, high directivity collimator. Methods (b) and (c) are mentioned for completeness; they have major practical disadvantages, so they will be discussed only briefly.

5.1. Atmospheric Optical Communication Systems

The beam from the laser and modulator is passed through lenses to focus it accurately and then sent through the atmosphere to a receiving detector at a distant point. Because of coherence, a 1 cm diameter beam only diverges to about 3 cms over 10 km, so that very little of the power is lost by divergence. The receiver must be accurately placed, because the beam is so narrow. Links of this type for ranges up to 3 km have been built and are quite practical.[9,10,25,26] Under good conditions an attenuation of 2 dB/km can be obtained. Various factors must be taken into account when assessing the attenuation. Firstly the atmosphere has certain absorption bands caused by resonances of water and carbon-dioxide molecules and 'windows' where there is relatively little loss. Fig. 5, taken from reference 14, shows the distribution of absorption throughout the optical spectrum. From this it is clear that in the infra-red region around 3·5 µm and around 10 µm the atmosphere is relatively loss-free.

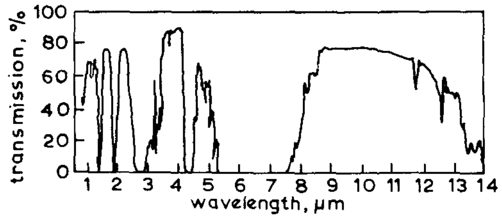

Fig. 5. - Measured transmission/wavelength for a 1 mile path in the earth's atmosphere under clear weather conditions (Ref. 14)

The effects of rain, fog and snow[14] must also be considered. Unfortunately these can be serious and are unpredictable. In the infra-red region an additional attenuation of up to 20 dB/km or more may occur in a bad fog, and up to 8 dB/km in rain. The visible region is worse in rain and much worse in fog. Prediction of the percentage of time an atmospheric link may be unusable requires a knowledge of the statistics of rain, fog and snow for the area concerned.

One other factor which does not affect the attenuation but affects the stability of the beam is temperature changes in the atmosphere. Temperature gradients change the air density and hence the refractive index of the air. These may occur over a large or small area. This bends and distorts the uniformity of the beam and must be allowed for either by making the receiving aperture greater than the nominal diameter of the beam or by making the beam more divergent. Small beam bending and non-uniform signal strength over the area of the beam are thus offset.

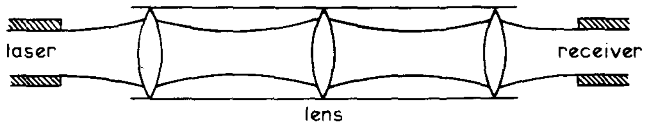

Fig. 6 - The confocal lens guiding system

5.2. Confocal Lens Systems

The beam is focused by a series of lenses enclosed in a hollow tube (Fig. 6). The convex lenses are spaced so that their distance apart, D, is equal to $\frac{1}{2}d^2/\lambda$, where d is the lens diameter and the focal length is ½D. All the light is then transmitted from one lens to the next. The losses could be as low as 1 dB/km. The disadvantages are that the lenses must be accurately placed, bends are difficult to negotiate, and since temperature variations deflect the beam, the pipe must be evacuated or filled with gas. If a system were installed, even very small disturbances in the surface of the earth would upset the lens positions and therefore make it necessary to fit servo systems on to some of the lenses. The system has been tried,[16] and losses of only 0·5 dB/km were obtained. This method is very good because virtually unlimited bandwidth is available, but also very expensive.

5.3. Reflecting Pipes

Hollow, circular, highly reflecting metal pipes a few centimetres in diameter are used to guide the light beam. The electromagnetic wave follows a zig-zag path by multiple reflection from the walls of the pipe. In this way energy is propagated along the guide. Reflecting pipes were one of the first methods considered for optical communications.[13,15] Their major disadvantage is that it would be extremely difficult to polish the surface to the accuracy required at optical frequencies. Also the reflection loss of a metal surface is proportional to the square root of frequency and therefore may be 100 times worse than at microwave frequencies. Typical losses would be 10 – 100 dB/km. It would be very difficult to negotiate bends because of the delay distortion introduced by the different path lengths around the bend. Glass tubing has also been used to propagate the rays,[20] but this suffers from the same disadvantages and is impractical for an engineered system, except over short distances.

5.4. Optical Glass-fibre Guides

The optical waves are guided along a thin fibre of glass, a few microns in diameter. This system seems to be the best of the various possibilities although the technology is by no means sufficiently developed to permit a practical system at the present day. The advantages of fibre-guides are that they are small (many fibres could be placed within the cross section of a coaxial cable), fairly easy to manufacture and very flexible. Also the guide can be bent without affecting the performance, since a bend in practice has a radius large compared with the fibre diameter and very large compared with an optical wavelength. There are two possible types of fibre guide, (a) over-moded guides, and (b) single-mode surface-wave fibre guides.

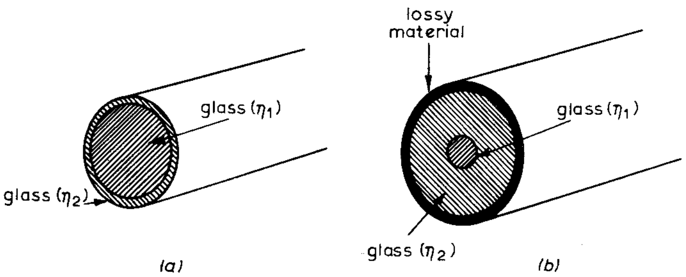

Fig. 7 - Optical waveguide

(*a*) Overmoded glass-fibre guide (*b*) Single-mode glass-fibre guide

5.4.1. Overmoded Glass-Fibre Guide

The cross-section is shown in Fig. 7(*a*). A core of about 70 microns is surrounded by a cladding of about 5 microns thickness made of glass with a refractive index such that total internal reflection of the light takes place in the core. Many hundreds of separate modes will propagate along this guide because it is many wavelengths in diameter. The multi-mode guide has been in use for a long time, but with an attenuation of the order of 1000 dB/km, its use has been restricted to transmission over a short distance. They are very cheap to manufacture and normally hundreds of fibres are placed in a plastic sheath and sold for a few shillings per foot. If the loss in the glass is improved to 200 dB/km it should be feasible to propagate pulses with a repetition rate of 5 MHz in 1 km of fibre.[19] A limitation is set by cross-coupling between modes, dispersion in the fibre, and scattering at the glass interface, rather than by the loss in the glass. Roughness of the surface can cause the light to escape from the core. For transmission lengths of a few metres, overmoded fibre offers the best and cheapest system. In principle the characteristics could be improved by reducing the diameter of the core, but then the power density would become very high and the tolerances more acute.

5.4.2. Single-Mode Surface-Wave Fibre Guide

The cross-section is shown in Fig. 7(*b*). A core of a few microns in diameter is surrounded by a cladding of about 100 microns. The refractive index of the cladding is about 1% less than that of the core (refractive index approximately 1·5). The structure then acts like a dielectric rod in free-space and, if the geometry is chosen correctly, only the predominant surface-wave mode is propagated along the structure.[17] The electromagnetic field is carried partially inside the core and partially in the cladding. The external field is evanescent in the direction normal to the direction of propagation, decaying exponentially along outward radials. In theory the cladding should be big enough to allow the field to decay nearly to zero; but this is not practical so that it is coated with some lossy material. When the frequency is chosen so that it is just below the frequency at which higher order modes begin to be propagated the dispersion is small and acceptable. The attenuation of the wave depends almost entirely on the absorption in the glass. If a glass with a loss of 10 dB/km could be obtained the bandwidth would be 1 GHz. Clearly this is a very wide bandwidth and makes this particular fibre guide a very attractive proposition. There is a limitation on the amount of power which could be fed into such a guide. 80% of the power is in the core and assuming a maximum power density of 50 MW/cm^2, the maximum permissible power input for λ_0 = 0·74 microns is 1 watt.[17]

Unfortunately glass with a loss of 10 dB/km does not exist at present (see Section 5.4.4) but this appears to be the only major disadvantage. The best glass fibres available at present have an attenuation of about 200 dB/km with a bandwidth of a few MHz. The manufacture of the glass-fibre is more difficult than the multi-mode fibre because both glasses have to be of low loss. There are also minor problems of the effects of ellipticity, uneven guiding surface, inhomogeneous glass and mode stability to be investigated. If glass with a low loss can be produced (and there are good reasons to suppose that it will be) the system is ideal for optical communications.

5.4.3. Launching the Laser Beam into the Fibre

In both types of fibre guide it is important to launch the light from the laser into the fibre correctly. For the multi-mode guide, light hitting the end of the fibre at an angle will suffer considerably more scattering than light entering parallel to the guide. With the single-mode fibre it is important to excite only the predominant mode. If a GaAs laser is used as a source it could be placed up against the end of the guide, although it might be necessary to have a tapering section of glass from the laser down to the core size of the fibre guide. The ends of the glass must be polished in order to ensure minimum reflection of light, but even so 5 to 10% of the light is reflected.

5.4.4. Absorption in the Glass

The success or failure of the fibre guide as an optical transmission medium depends on whether the bulk loss in the glass can be made small enough. The losses are caused partly by scattering which arises as a result of structural defects, particle inclusion, random fluctuations and lack of order in the structure of the material: and partly by absorption due to the natural vibrations of the molecules. Glasses available at present are not very pure and have a loss of between 200 and 1000 dB/km but, with the incentive to develop low-loss glass, much research effort is being applied to the problem. Losses of 10 dB/km have been measured on short lengths of quartz fibre in the laboratory which indicate that losses of this order may be attainable.

6. DETECTORS

Reception of the light beam at the far end of a communications chain, where the signal is weak, requires a device with a high gain and good noise performance. Three methods of reception exist:

(a) heterodyne
(b) carrier-frequency pre-amplification
(c) direct detection

All three have similar potential at visible wavelengths because basically all optical receivers are quantum-noise limited (in detectors the quantum noise is often referred to as 'shot' noise). The noise will be considered in Section 7. Detailed discussion of the different methods of detection is given in references 21 and 24.

6.1. Heterodyne Detection

The incoming signal is superimposed on a much larger local oscillator field generated by another laser near the detector input. The local oscillator has a frequency which is close to the frequency to be detected and the information is extracted by some form of simple photodetector at the difference frequency. This avoids any distortion of the a.m. signal and is inherently 3 dB better in signal-to-noise ratio than direct detection. However the local oscillator light beam and the input signal beam need to be accurately aligned at the face of the detector; also, the extra laser and associated lenses could be bulky and expensive.

6.2. Carrier-Frequency Pre-amplification

The light beam is passed through a laser acting as an amplifier with a gain sufficiently high to make any noise introduced in the subsequent detection process harmless. A laser acting as an amplifier has less feedback than one used as an oscillator. The helium-xenon laser can provide a gain of about 400 dB per metre of laser length, but with only a few milliwatts output power, or the carbon-dioxide laser provides about 2·0 dB/m with up to 200 watts output power. Gas lasers acting as amplifiers are usually bulky and require much support equipment.

6.3. Direct Detection

The two previous methods suffer from the same disadvantages of size and expense, the ultimate requirement being a device which will detect the light directly and have built-in amplification. Most direct detectors (i.e. photodetectors) have only low gains and relatively high noise level although devices with better characteristics are being continually developed. They detect the envelope of the modulated signal and may cause distortion; also they may introduce thermal noise because of their finite resistance. However, they are usually compact and there are no problems of aligning the light beam. A photodetector is, of course, necessary even with the first two methods of reception, but here the object is to provide a strong signal which over-rides the noise. The various types of photodetector are outlined below.

6.4. Photodetectors

Photodetectors may be vacuum detectors or solid-state detectors. Only a very brief outline of a few of the more common and potentially useful detectors will be given; detailed discussion of all available types is given in reference 21. Only a qualitative assessment of their performance is given since performance can vary considerably.

(a) Photomultiplier: Uses photo-emission of electrons and an electron-multiplier to achieve amplification. Very sensitive and the best existing choice for laboratory work. Occupies a few square inches.

(b) Travelling-wave phototube: The laser beam falls on a photo-electric cathode, this creates an electron beam which interacts with a helix slow wave structure. The helix acts as a distributed output coupler and extracts the modulation from the beam. Very sensitive band-pass detector and high frequency response (10 GHz). Requires very high voltages.

(c) P-n junction photo-diode: Photons of incident field release charges which are swept out by a biasing field creating a low-frequency current. Small, cheap, good high-frequency response, not very sensitive.

(d) Silicon and Germainium avalanche photo-diodes: Uses impact ionization in the high field region of a reverse-biased p-n junction. Silicon avalanche photo-diodes have the highest gain-bandwidth product of any solid-state photo-detector. They are only a few microns in diameter so can be butted on to the end of a glass-fibre cable. Still undergoing development but potentially the most promising detector for optical communications.

7. NOISE

In all communication studies the balance between output signal and output random noise must be considered in relation to the type of signal being transmitted, the method of modulation used and the amount of noise which can be tolerated on the final output. For the present purpose the transmitted information will be taken to comprise a television signal capable of reproducing a 625-line colour picture. It can be assumed that the television signal is encoded to produce an information rate which does not exceed 100 Mbits/sec.

When estimating optical link performance, the noise contribution of the transmitter can sensibly be neglected, the significant factor being the noise generated in the light detector at the receiving terminal. In this respect the optical link is similar to the radio link in which the signal-to-noise ratio also is largely determined by the initial stage of the receiver. As the characteristics of radio links are well known it is useful to compare them with optical links. The following approximate argument only considers the effective noise power as it appears at the output of a basic detector when the signal output is a d.c. current proportional to incident signal power. The intention is to assess the magnitude of signal power required.

When considering detectors of electro magnetic waves in general terms, two fundamental types of noise must be taken into account in assessing the signal/noise ratio at the output,[28] namely, thermal noise and quantum noise.

The thermal noise, which is caused by random free electron motions in conductors, has a power spectrum which is substantially constant up to 1 THz, decreasing sharply with increasing frequency above this value. At low frequencies (including microwave frequencies) the noise power per cycle of bandwidth is approximately equal to kT where k is Boltmann's constant (1·380 x 10^{-23} joule/degree K) and T is the absolute temperature. At room temperature (i.e. at 290°K) the kT noise power has a value of 4 x 10^{-21} watts/Hz and this can be taken as a reference level in making the comparison.

The quantum noise power is caused by the discrete nature of the incident signal upon the detector. For direct optical detectors the output signal current is proportional to the incident signal power and assuming 100% conversion efficiency it can be shown that the effective noise power per cycle at a detector output is independent of received power level and equal to $2h\nu$ where h is Plank's constant (6·626 x 10^{-34} joule-sec) and νHz is the frequency. As the effective thermal noise power decreases and the effective quantum noise power increases with frequency, the former is predominant in microwave systems and the latter in optical systems. Figure 8 shows the total effective power spectrum per cycle for the sum of thermal noise at room temperature and quantum noise expressed in decibels relative to 4 x 10^{-21} watts/Hz. It will be observed that this curve has a sharp knee between the straight portions which corresponds to the frequency at which thermal and quantum noise contributions are approximately equal. Practical signal/noise ratio performances, however, are limited by detector efficiency, whereas the thermal and quantum noise power mentioned above assume 100% efficiency. Also, in optical detectors, where quantum noise is usually predominant, the output signal power considered may include a component due to unwanted ambient light falling on the detector. The useful signal/noise ratio will therefore be reduced if this component forms a significant part of the output.

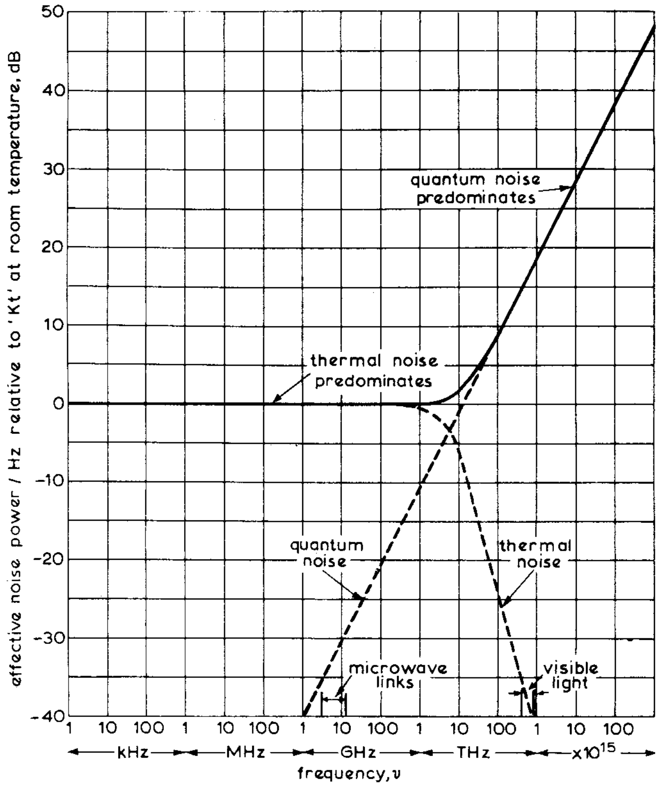

Fig. 8 - spectrum of effective noise power in detectors

At room temperature, the fundamental noise in an optical detector is 20 dB above that in a microwave link detector (Fig. 8). Practical detectors are at present inefficient and optimum performance is far from being attained. Present day optical detectors are about ten times less efficient than radio detectors operating in the microwave region. Optical receivers therefore have overall signal-to-noise performance about 30 dB less than microwave link receivers given equal received powers.

A conventional contimetric radio link using frequency modulation requires about 10 nW of mean input power per television channel. An optical link with the same modulation would therefore require some 10 μW per channel. The modulation system actually used and possible improvements in detector efficiency may modify this figure but it serves to put the situation in perspective.

8. THE LINK SYSTEM IN GENERAL

The compact and robust solid state laser appears to be the most attractive transmitting device for general application in the future, both in guided systems and in short links through the atmosphere. At the present, room temperature GaAs lasers can operate only with short pulses and take high currents. This means that they cannot be contemplated for p.c.m. operation in a wide-band system, because permissible duty ratios of only 1 : 200 are possible. Assuming that all signal levels are equally likely, the unity mark/space ratio p.c.m. encoding requires an average duty ratio of 1 : 4. In terms of a single pulse-modulated laser this implies that almost continuous operation is required, even for p.c.m. Some relaxation is possible if a number of lasers are used, one for each digit for example, the pulsed outputs being interlaced in time. For the receiver terminal direct detection will probably prove to be better than heterodyne detection. Future repeaters in link systems will probably comprise a direct detector, pulse cleaning and amplifying circuits and a solid state laser. The practical use of optical links for television therefore depends on fundamental development in continuously operating, room temperature solid state lasers and fibre guides. Improvements in direct detectors will also probably be made.

9. COMPLETE COMMUNICATION SYSTEMS: POSSIBLE USES

When a link is designed to fulfil a specific task, attention must be paid to bandwidth, distance and environment. The type of system will depend on whether the link is to be used for speech, telemetry or television and whether guided or free-space propagation is being considered.

The most stringent requirements are set by a permanent high capacity, long-distance link designed for p.c.m., such as might be used for conveying many television and telephone channels between two centres. Reliability is important in this application. The best combination would seem to be a pulsed GaAs laser, a single-mode glass fibre guide and silicon avalanche photo-diode as a detector. Repeaters would be needed every 1 or 2 km. Such a system with 1 GHz bandwidth and 100 mW power from the laser can withstand a loss of 45 dB/km. Since this is considerably greater than the anticipated loss in high quality quartz glass-fibre (see Section 5.4.4) there are no theoretical reasons why the system cannot be built. It should not be many years before such a system becomes practicable. It may then be an economical alternative to the standard coaxial or microwave television links because of the very large information capacity. A bundle of fibreguides can occupy the area now taken up by a coaxial cable, so the information capacity per unit area of cross-section will be very great.

For shorter distances, say less than a few hundred metres, the same system would still be best for p.c.m., but for a single a.m. television channel or a number of a.m. speech channels, the multi-mode fibre with the same source and detector could be slightly cheaper. By using one of these systems, the complex mass of coaxial cables now threading through many buildings could be reduced to a single multi-fibre cable about one centimetre in diameter. The terminal equipment could be made equally compact by using solid-state lasers and photo-diodes.

Free-space optical communication links are of two kinds: those which are intended to be permanent, such as a direct link between two transmitting stations, and those required for a few hours only (for instance, sound or vision communications in studios, television links between a radio camera and control vehicle or links required to span a road when it is inconvenient to put video cables across it).

The advantages of free-space optical links are that they are simple, and only the terminal equipment requires maintenance. They have a bandwidth limited only by the terminal equipment, and do not interfere with any other communications links. This last advantage is particularly important when the frequency spectrum is so overcrowded. The major disadvantage of outdoor links is their dependence on weather conditions. Permanent optical free space links will probably never be built (through permanent links in space between satellites or manned space-crafts are definitely feasible). The problem of weather is not so acute for temporary links, especially those being used in conjunction with a television outside broadcast, since weather conditions which upset the optical link are also likely to prevent television altogether.

With a free-space link, a narrow beam from the transmitter must be received accurately. This means that both the transmitter and receiver must be fixed and pre-aligned, or else that some form of servo-system must be used on the transmitter to ensure that the beam is always pointing at the receiver. This could be done by a simple gallium-arsenide light source at the receiver and a small matrix of photo-detectors at the transmitter feeding into a servo-system. Alternatively, a high power laser could be used, with a wider beam. Thus a gas laser would be required; for a temporary installation the normal difficulty of unreliability would not be as important.

The likely performance of free space optical links can be illustrated by comparing a 3 km link in clear daylight conditions and a short 30 metre link in a colour television studio. Both links are intended to carry a television signal with 8 MHz base-bandwidth and 50 dB signal/noise ratio. The operating wavelength could be chosen in the infra-red region at 1 μm. The receiver could consist of a silicon avalanche photo-diode placed behind a lens system with a captive area of 10^{-3} m^2 and a 1° beam. The total noise power at the receiver terminals would then be about 0·1 μW in the television studio and 0·05 μW in daylight. The difference is caused by the higher background light in the studio. Then the optical power required at the receiver input would be about 10 μW for both cases.

10. CONCLUSIONS

Optical links will probably be used in the future for carrying television and multi-channel telephone circuits over considerable distances using fibre guides. Links through the atmosphere will have only a limited application because of unavoidable absorption by rain and fog. Nevertheless, for short ranges, the advantages conferred by light weight and immunity from interference and distortion could make them attractive in certain situations. The very large bandwidth which is theoretically available from optical links has probably been the principal spur to development, but the technology is still in its infancy and much work will be necessary if the full potential is to be realised. In the U.K. current research is mainly concerned with the improvement of the materials and manufacturing techniques of glass fibres to reduce attenuation to manageable proportions, and the development of solid state lasers which will operate at room temperature at pulse rates suitable for the information capacity required by television and multichannel telephone circuits.

The most important application for broadcasting authorities is probably for short outside broadcast links. But the possibility of using optical radiation in television studios for sending timing signals to cameras and for receiving picture information should not be overlooked. It appears that useful work in the broadcasting field must await the outcome of the more fundamental researches and that little can be done at present beyond keeping a watch on these developments.

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